California semi truck electrification: Preliminary assessment of infrastructure needs and cost-benefit analysis

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Executive summary

- Electrification presents a major opportunity to address greenhouse gas emissions and air pollution from heavy-duty trucking in California
- Here we provide a **preliminary estimate of infrastructure needs and economic impacts** of electrifying combination trucks in California
  - Electrifying CA trucking is estimated to require ~**750 charging** stations at a **$10.8B** upfront investment
  - Baseline costs of electrification (including charging infrastructure, grid upgrades, electricity, and truck electrification) is estimated to be **$5.7B/yr**
  - Baseline savings on diesel, GHG emissions, and air pollution is estimated to be **$7.8B/yr**
  - **Net savings from electrification of combination trucking in CA is estimated to be $2.2B/yr**

Opportunity for truck electrification

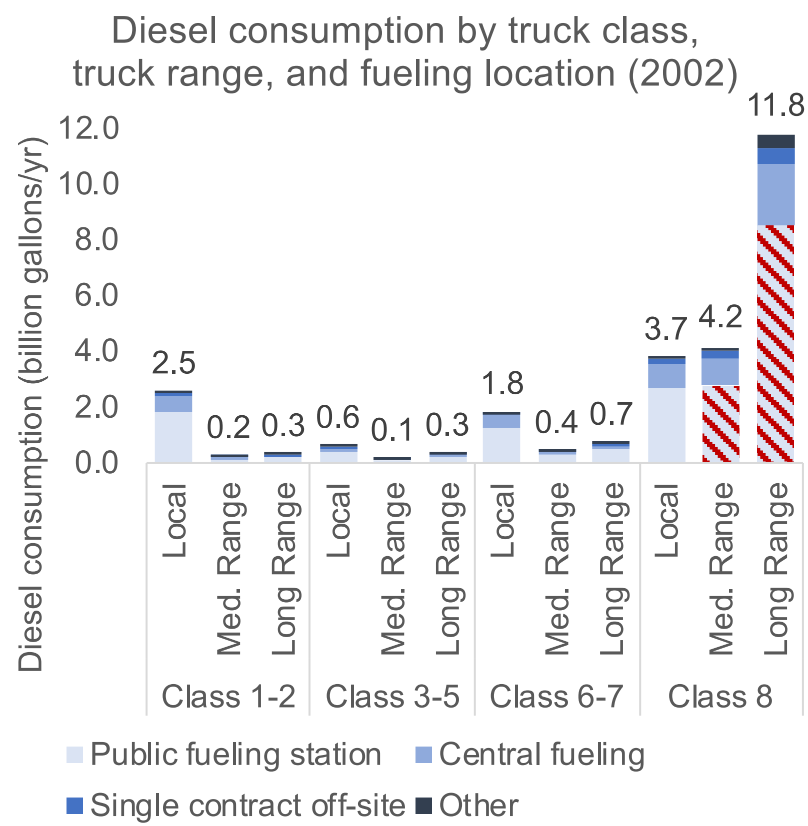
Electrifying heavy-duty trucking has the potential to address air pollution and GHG emissions, and is becoming feasible as battery costs fall

- Electrification of trucking in California presents a major opportunity to address air pollution and GHG emissions
  - Heavy-duty trucking accounted for **8% of CA's GHG emissions** in 2016
  - Heavy-duty trucking accounted for **27% of CA's NOx emissions** in 2015
  - Combination trucks (semi trucks) are responsible for an estimated **60%** of GHG and NOx emissions from heavy-duty trucking
- Truck electrification has been seen as challenging, but recent developments suggest that it is becoming more feasible:
  - **Battery costs are falling:** lithium-ion battery prices were $175/kWh in 2017, an 80% drop from their cost in 2010; BNEF projects a cost of $100/kWh by 2026
  - **Generation costs are falling:** The cost of electricity generation is dropping as wind and solar prices have become cheaper than coal and gas
- Truck OEMs are coming out with new electric models
  - At least **17 heavy-duty models** have been introduced since 2017

Specifying "trucking"

In this analysis, we explicitly address combination trucks, though electrification of other classes of trucking merits exploration as well

- As battery costs fall, opportunities are opening up for electrification across many different types of vehicles
- In this analysis we quantify the electrification opportunity for **medium- to long-range combination trucks (i.e., tractor-trailers, "semis") fueling at public stations**
  - This category alone accounts for **40%** of all diesel consumed by trucks
  - These trucks are Class 8 heavy-duty vehicles



1. Estimating Charging Infrastructure Needs

Infrastructure needs: energy requirements

Electrifying combination trucks in California would require 20 TWh/year, equivalent to 9% of California's electricity usage

- Combination trucks currently account for an estimated **9,300 million vehicle-miles traveled (VMT)** per year in CA
  - 78% of miles are traveled on roads that see at least 3000 heavy-duty trucks/day
  - On-road freight transport is expected to rise in the future
- To electrify all combination truck VMT in California would require **20 TWh/year***
  - This figure represents 9% of the energy usage of California in 2017 (206 TWh)
  - Fuel efficiency (either electricity or diesel) varies based on payload; VMT-based energy requirements should be taken as estimates based on averages

Representation of heavy-duty truck flows in CA in 2012

>3000 trucks/day

**Electric fuel efficiency is estimated by CARB to be 0.48 mi/kWh for a regional tractor*

Infrastructure needs: charging stations (1/2)

To estimate truck charging infrastructure requirements, we modeled fast-charging stations able to simultaneously charge 10 trucks

- We model truck charging stations with the following characteristics:
  - **~20 MW** total capacity
  - **10-truck** simultaneous charging capacity, assuming 1-MWh battery/truck* and 75% depth of recharge
  - **30-minute** charging time (DC fast charging)
  - **20%** utilization rate**
  - **Transmission**-connected
- **Utilization rate**: represents hours trucks spend charging per day out of 24 hours
  - E.g., modeled charging station operating at a 20% utilization rate would deliver 72 MWh/day (i.e., would charge 96 trucks/day) out of a potential 360 MWh/day

**1 MWh battery corresponds to calculated capacity of Tesla 500-mile-range truck; model outputs do not change if smaller batteries are assumed*

*** Estimate based on current car DCFC utilization rate from Fitzgerald et al. (14%) and capacity factor assumed by Tong et al. under high alternative truck fueling penetrations (40%)*

Infrastructure needs: charging stations (2/2)

An estimated ~750 charging stations would be needed to meet the energy needs of electrified trucking in California

- An estimated ~**750** charging stations would be needed to meet the energy needs of heavy-duty trucking in California
  - Assumes 20% station utilization rate
- While only a first-order estimate based on energy consumption, this estimate reflects certain important aspects of trucking in California
  - **Fueling behavior:** Models on-the-road fueling (rather than centralized fleet fueling), which account for **71%** of diesel sold to heavy-duty trucks
  - **Major highways:** Does not address station distribution in sparsely-traveled areas, but provides representative estimate given that **78%** of VMTs are traveled on major corridors
- Exact number of stations required for full electrification depends on truck flows and driver behavior, which merit further study

2. Estimating Costs and Benefits of Electrification

Costs and benefits of electrification

The cost of charging infrastructure, electric trucks, and electricity are weighed against avoided diesel spend, GHG emissions, and air pollution

- We attempt to estimate the net benefit of truck electrification to the state of California
- We account for three major costs
  - Charging station and grid infrastructure cost
  - Electricity cost
  - Incremental cost of battery-electric trucks over diesel trucks
- We account for three major benefits
  - Avoided spending on diesel fuel
  - Avoided greenhouse gas emissions
  - Avoided air pollution damages

Cost-benefit analysis: charging infrastructure (1/2)

The cost of charging station infrastructure to support electrified trucking in California is estimated to be $1.0B/yr

- We estimate the cost of a ~20-MW charging station to be **$15 million upfront and $210,000/yr***
  - This figure includes the cost of land, electric vehicle supply equipment, installation, and a transmission-level grid connection
- Total upfront cost of charging infrastructure needed in California to meet energy needs of combination trucks is estimated to be **$10.8B**
  - Estimate reflects 20% utilization rate
- On an annualized basis, charging infrastructure cost is estimated to be **$1.0B/yr****

**See appendix for more detail on infrastructure cost estimation*
***Assumes 5% discount rate, 20-year station lifetime*

Cost-benefit analysis: charging infrastructure (2/2)

Transmission grid upgrades to support new electric trucking load are estimated to cost $1.1B/yr

- An important aspect of charging infrastructure is transmission grid upgrades that may be needed to support new trucking load
- An estimated **$7.3B total**, or **$1.1B/yr,** of transmission upgrades would be needed to support electrified trucking
  - Transmission cost taken as $520,000/MW or $76/kW-yr*
  - Actual cost is highly dependent on station siting
- Together, station infrastructure and transmission infrastructure cost is estimated to be **$2.1B/yr**

Baseline charging infrastructure cost: $2.1B/yr

**From CPUC RPS Calculator V6.2; median of California transmission cost estimates. Annualization factor 14.5%*

Cost-benefit analysis: electricity cost

Electricity cost for electric trucking is estimated to be $2.2B/yr, but depends on tariff structure and time of charging

- Trucks may act as flexible loads that can charge when electricity prices are low and the grid is less constrained
- If charging occurs during the 8 lowest-cost hours of the day, average electricity price would be **$110/MWh** as a customer of SCE, which would make electricity cost for electrified trucking **$2.2B/yr**
  - Reflects 20% utilization rate
- Electricity cost can vary based on several factors
  - **Electricity provider:** purchasing electricity from IOU vs. directly from wholesale market
  - **Time of day**: electricity prices tend to be higher on-peak (e.g., 4-7 PM on weekdays) and lower off-peak (e.g., overnight or during high solar production)
  - **Demand charges**: per-kW demand charges are a common component of electricity tariffs that drive up electricity costs at low station utilization
- Electricity prices as a CAISO direct-access customer could be as low as **$38/MWh** with modification of demand charges to be peak-coincident

Baseline electricity cost: $2.2B/yr

Cost-benefit analysis: incremental truck cost

The incremental cost of electric trucks over diesel trucks is estimated to be $1.4B/yr

- The battery in an electric truck is the major driver of the cost increase of electric over diesel trucks
  - $100/kWh battery costs are expected by Tesla by 2020 and by BNEF by 2026
  - At this battery cost, a 1000-kWh truck battery will cost **$100,000**
- However, electric trucks realize incremental savings over diesel in the diesel engine, transmission, and drivetrain which amount to **$22,000**
- Electric trucks also realize lower lifetime maintenance costs than diesel trucks, which are not taken into account in this analysis
- Average battery depreciation cost is estimated to be **$0.15/mi***
  - Assumes 75% battery depth of discharge and 2000 cycle life
  - Battery treatment (depth of discharge, state of charge parameters, temperature) has major impact on lithium-ion cycle life and depreciation cost
- Electrifying all miles driven by combination trucks in California would equates to **$1.4B/yr** in net incremental electrification cost

Baseline incremental truck cost: $1.4B/yr

**Assumes 68,000 miles/year; 1,000,000 mile lifetime for diesel truck. Estimated over lifetime of diesel truck*

Cost-benefit analysis: avoided diesel spend

Combination trucks spend an estimated $5.0B/yr on diesel that could be avoided with electrification

- Assuming combination trucks achieve 5.87 mi/gal on average, an estimated **1.6B gallons** of diesel per year are consumed by combination trucks in California*
- This equates to an estimated **$5.0B/yr** spent on diesel at $3.16/gallon

Baseline diesel savings: $5.0B/yr

**Assumes all combination trucks use diesel*

Cost-benefit analysis: avoided GHG emissions

Avoided GHG emissions from electrifying trucking are worth an estimated $0.9B/yr

- Combination trucks in CA emitted an estimated **20 million tonnes (MT)** of CO_2e in 2016 (**5%** of total state emissions)
- GHG emissions reduction benefits depend on:
  - **Emissions intensity of electricity** (currently 0.24 tonne CO_2e/MWh; expected to be 50% renewable by 2030 and carbon-free by 2045)
  - **Social cost of carbon** (at baseline taken as $52/tonne*; cost varies substantially by year and by assumed discount rate)
- Eliminating GHG emissions from combination trucks in California is valued at **$1.0B/yr**
- Emissions from charging trucks with 50% renewable power are estimated to cost **$170M/yr**, making net GHG benefits of electrification **$0.9B/yr**
- Near-term benefits can be increased if charging is done at hours where low-carbon energy is marginal

Baseline GHG savings: $0.9B/yr

Social cost of carbon at 3% discount rate, 2020 estimate, 2019 dollars

Cost-benefit analysis: avoided air pollution

Net air pollution savings from electrification are estimated to be $1.9B/yr

- Diesel trucks emit a range of pollutants including NO_x, PM2.5, ROGs*, ammonia, and SO_2
  - Heavy-duty diesel vehicles in California substantially and disproportionately contribute to NO_x pollution
  - CARB: "The estimated contribution of on-road heavy-duty diesel vehicles to the total NO_x emission in California was ~32% in 2016, which is considerably higher than the US average (~16-18% in the past decade)"
- Eliminating emissions from heavy-duty diesel trucks in California in 2016 would have an estimated value of **$2.0B/yr** (79% of which comes from eliminating NO_x)
- After accounting for increased power sector emissions to fuel electric trucks, net air pollution savings from electrification are **$1.9B/yr****

Baseline air pollution savings: $1.9B/yr

**This analysis draws on nationwide figures that estimate damages from volatile organic compounds (VOCs), rather than reactive organic gases (ROGs) in California; here we have assumed per-ton ROG damages to be equivalent to per-ton VOC damages*

***Assumes marginal NOx/SOx emissions intensity is equal to current CA average emissions intensity*

Cost-benefit analysis: baseline total savings

California stands to realize $2.2B/yr in net benefits with fully electrified combination trucks

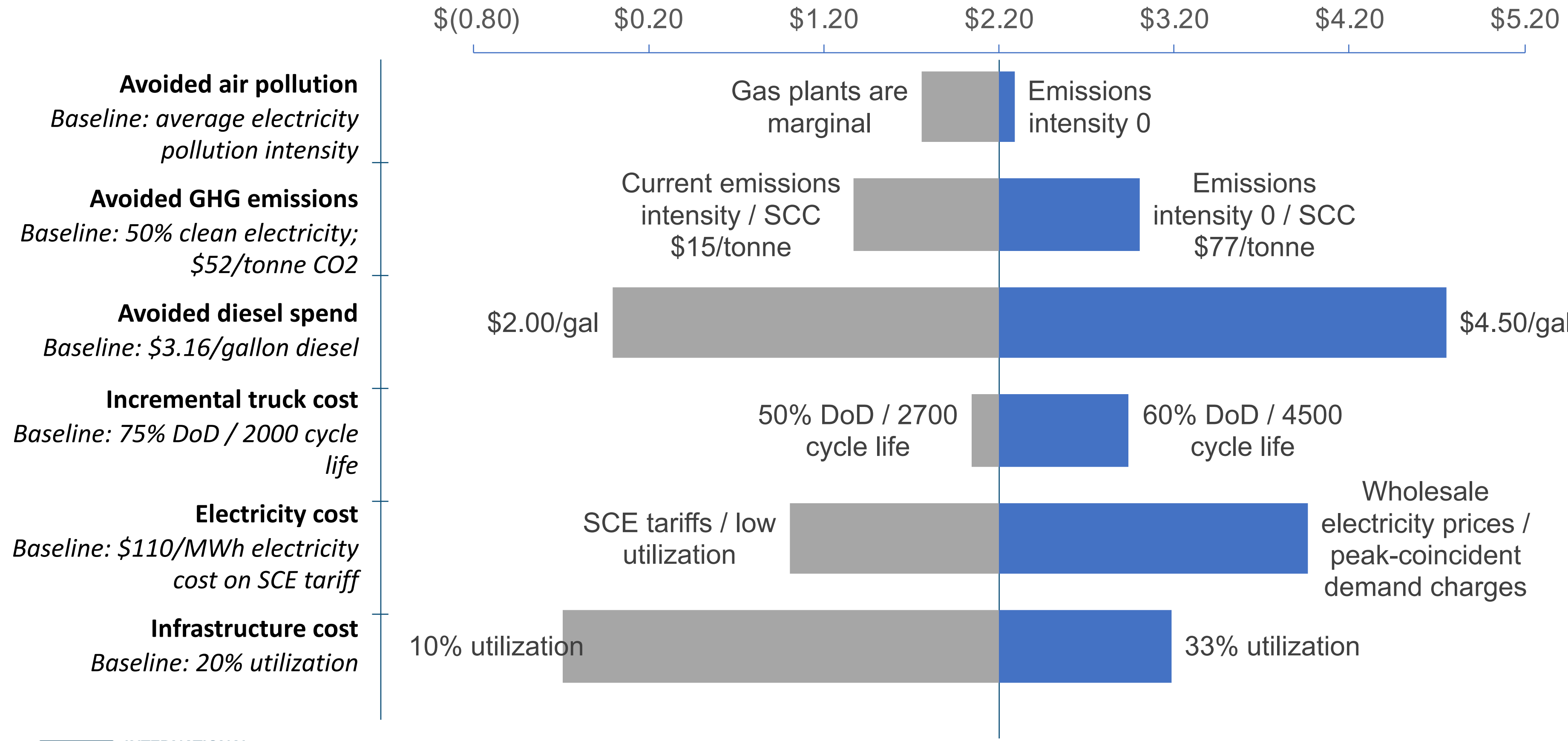
Baseline cost-benefit analysis results

Category	$B/yr	Baseline assumption
Costs		
Charging/grid infrastructure	$2.1	20% utilization rate
Electricity	$2.2	$110/MWh electricity cost (incl. demand charges) as SCE customer
Incremental truck cost	$1.4	
Total costs	*$5.7*	
Benefits		
Avoided diesel spend	$5.0	$3.16/gallon diesel
Avoided GHG emissions	$0.9	50% clean electricity; $52/tonne carbon cost
Avoided air pollution	$1.9	Gas plants are marginal during truck charging
Total benefits	*$7.8*	
Net benefit	***$2.2***	

Cost-benefit analysis: sensitivities (1/2)

Net benefit of truck electrification is sensitive to key variables, potentially ranging from -$3.9B - $7.9B/yr according to the sensitivities considered

Quantifying sensitivity of net benefit of electrification ($B) to key variables*



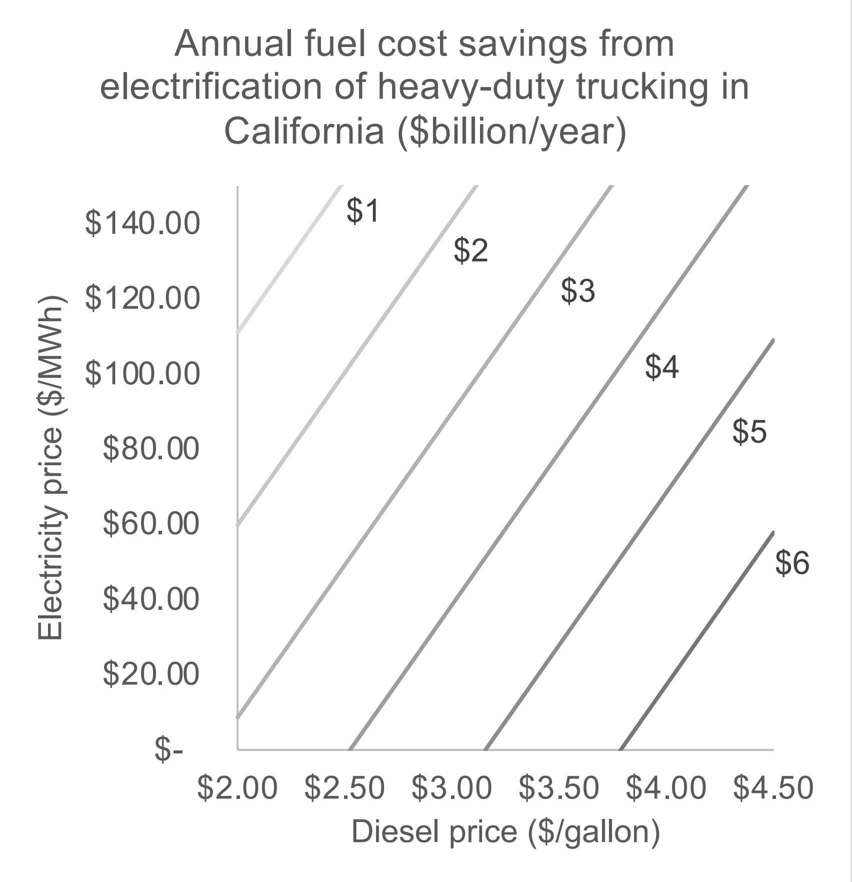
Net benefit of electrification at baseline = $2.2B/yr

*The variable under consideration is manipulated while other variables remain at baseline values

Cost-benefit analysis: sensitivities (2/2)

Even at low-end diesel prices and high-end electricity prices, fuel cost is roughly equivalent

- Diesel prices have ranged between \$2.00/gal and \$4.50/gal in California between 2009 and 2019
- Electricity prices are highly dependent on tariff structure and policy
  - Low-end prices of \$35/MWh could be achieved with wholesale price access, modification of demand charges to be peak-coincident, and off-peak charging
  - High-end prices of \$160/MWh will occur in SCE territory at low station utilization, even if trucks charge off-peak
- Even at a diesel price of \$2.00/gal and an electricity price of \$160/MWh, **electric and diesel fuel cost are roughly equivalent**



Further considerations

The evolution of key variables and implementation issues are both important to consider when evaluating costs and benefits of electrification

- This analysis does not account for evolution of key variables, but certain trends are relevant in considering the future value of electrification
  - **Total on-road freight VMT** are expected to increase ~75% from 2012-2045
  - **Charging infrastructure cost** is dependent on utilization rate and industry scale, both of which are likely to increase over time and drive down unit costs
  - **Electricity cost** under very high renewable scenarios is uncertain, but average wholesale electricity prices are expected to decline under 40-50% penetrations of wind and solar
  - **Diesel cost** is expected to rise modestly in real terms between 2018 and 2050
  - **Avoided GHG emissions** will be more valuable in the future; current estimates may change with greater understanding of climate impacts and discount rates
- Further research is needed to better understand charging infrastructure needs and costs and benefits of electrification
  - **Agent-based modeling** to site charging stations based on actual truck flows
  - **Power systems analysis** to understand grid upgrades required
  - **Electricity rate design** to optimize timing of charging

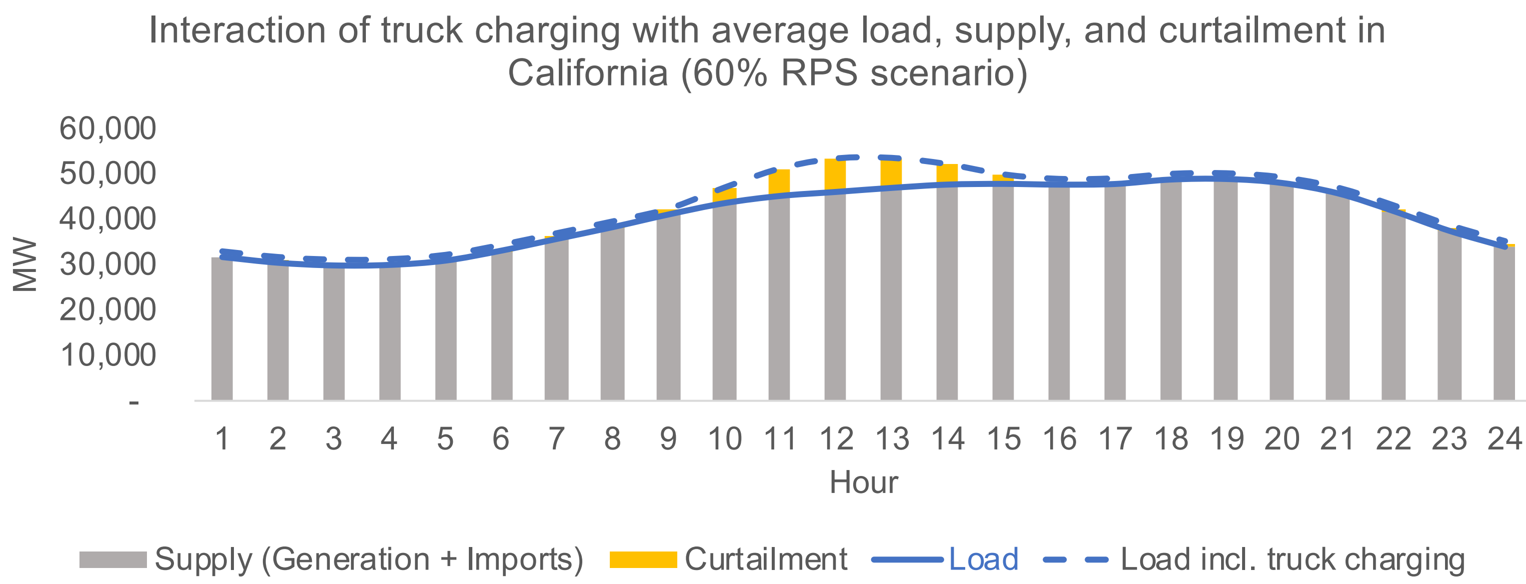
Electricity cost deep dive: trucking and curtailment (1/3)

We model two high renewable penetration scenarios to investigate the extent to which electric trucking could consume curtailed renewables

- Trucks are theoretically able to respond to price signals and charge at hours of the day where electricity prices are low
- One such opportunity is to charge during times of excess renewable energy production
- We model two high renewable energy penetration scenarios to investigate the extent to which truck charging could absorb curtailed renewable energy
  - Scenario 1: California meets 60% RPS target
  - Scenario 2: California meets 100% RPS target with 100 GW of wind and solar and 150 GWh of battery storage

Electricity cost deep dive: trucking and curtailment (2/3)

With a 60% RPS, if trucks charge during hours of excess solar production, curtailed renewables could meet up to 60% of trucking's energy needs

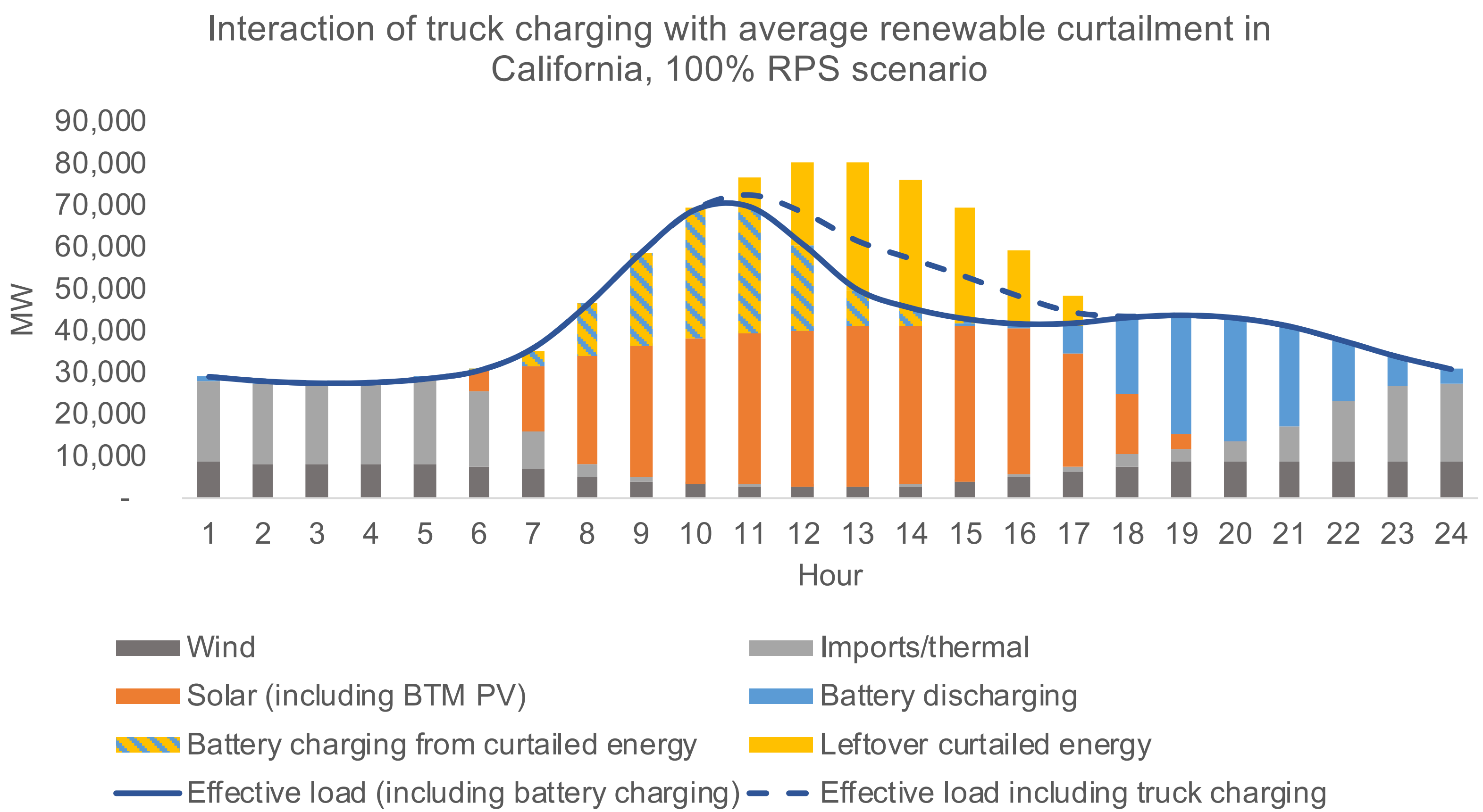


- With a 60% RPS*, curtailed renewable energy could meet **60%** of trucking's energy needs on average if trucks can charge during excess production
- Curtailed energy available varies throughout the year, only able to meet **8%** of trucking needs in December but **92%-150%** from March-June

**Modeled using PLEXOS*

Electricity cost deep dive: trucking and curtailment (3/3)

With a 100% RPS, if trucks can charge during hours of excess solar production, truck charging could absorb over 1/3 of curtailed energy



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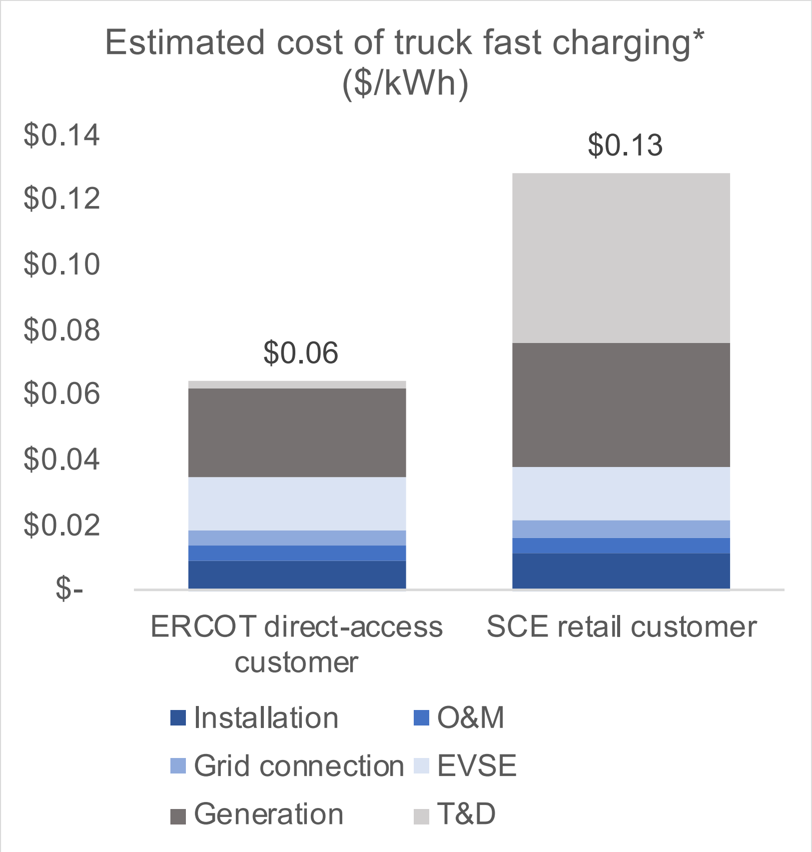
Appendix A: Estimating the Cost of Electric Truck Fast-Charging Stations

Truck charging cost components

Here we detail the costs of a 9.4-MW charging station with five 1.9-MW chargers

- **Key components** of truck charging cost:
  - Station costs
    - EVSE (truck charger)
    - Grid connection
    - Installation
    - Operations & maintenance
  - Electricity costs
    - Energy
    - Transmission & distribution
- Our modeling suggests that truck fast-charging can be achieved at a cost of **$0.06-$0.13/kWh**, depending on the state and electricity tariff structure
- **This presentation will detail the costs of electric truck charging stations** rather than electricity tariffs



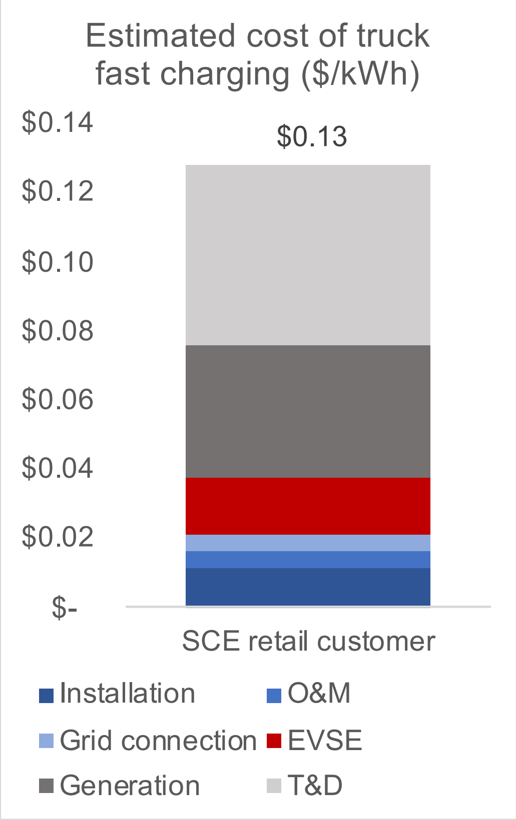
*Includes amortized infrastructure cost at 33% station utilization

Cost estimation: EVSE (truck charger)

We estimated the cost of each 1.9-MW DC truck charger from two complementary perspectives

Industry experience of DC station costs	Bottom-up estimate based on grid-scale S+S
We blended industry estimates of large fast charger costs with scaled-up costs of car-scale fast chargers. • Estimated hardware cost of 1.9-MW charger, provided via industry conversation: **$700,000** • Average estimated hardware cost of 50-120 kW car chargers: $511/kW → cost of 1.9-MW charger: **$960,000**	*The core element of a truck fast charger is an AC/DC power converter. The cost of grid-scale solar-plus-storage projects includes the cost of a bidirectional inverter as well as relevant balance-of-system costs.* • Inverter, structural BOS, and electrical BOS for grid-tied solar+storage project: $265/kW → cost of 1.9-MW DC charger: **$500,000**

Estimated 1.9-MW* truck charger cost: $670,000



**1.9-MW charger figures are based on needs for charging a 500-mile range Tesla truck estimated to have a 1-MWh battery to a 75% recharge in 30 minutes; for lower-range trucks, charger costs can be scaled down on a $/MW basis.*

Cost estimation: Grid connection

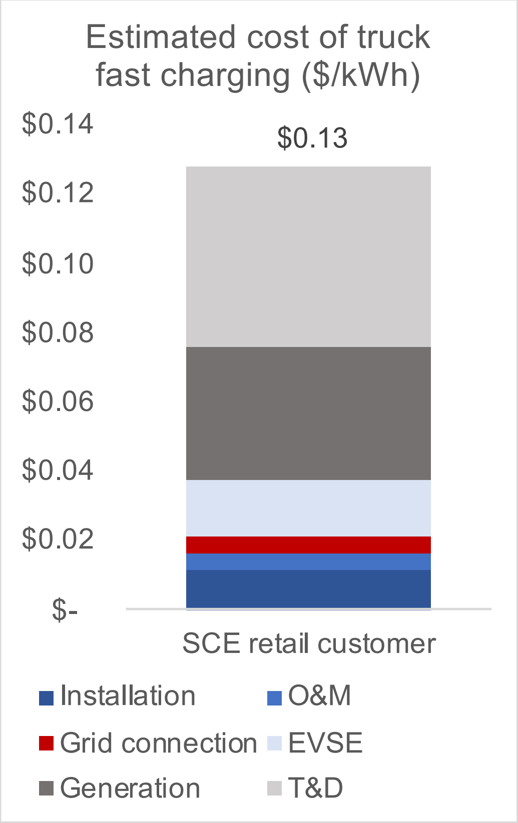
We used utility-scale solar PV grid connection costs as a proxy for charging station grid connection costs

Utility-scale solar PV grid connection costs

We used IRENA's 2016 estimate of US utility-scale solar PV grid connection costs. In our model, we assume the truck station is connected at the transmission level.

- Grid connection cost: **$144/kW**
- Grid connection lifetime: **30 years**

Estimated 9.4-MW grid connection cost: $1.3M

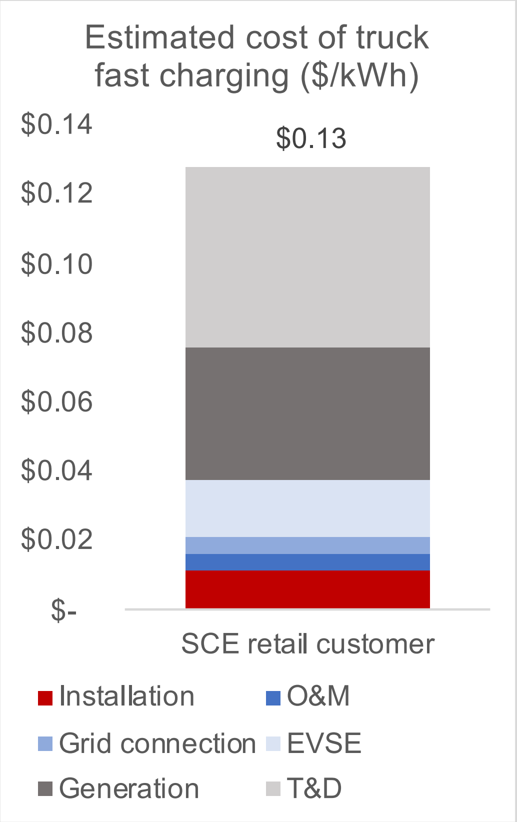


Cost estimation: Installation

We combined land costs and grid-tied battery installation costs to estimate truck charging station installation costs

Land costs	Grid-tied battery installation
We estimated the cost of land in both California and Texas by finding an average per-acre sale price of existing truck stops. We scaled that figure based on the estimated area needed for the charging station.* • Total cost of land in Texas: **$420,000** • Total cost of land in California: **$1.1M**	*We used installation costs associated with a grid-connected battery as a proxy for installation costs of a truck charging station.* • Installation labor and equipment: **$88/kW** • EPC overhead: **$49/kW** • Interconnection fee: **$29/kW** • Total installation cost: $167/kW → cost of 9.4-MW charging station: **$1.5M**

Estimated installation cost of 9.4-MW charging station: $2.0M - $2.6M



*Because these figures often include retail truck stop businesses in addition to land costs, they are likely inflated relative to land costs alone

Cost estimation: O&M

We estimated O&M costs by combining data from utility-scale PV systems, electric bus stations, and industry interviews

Electrical maintenance

For this figure we combined PMI costs from the Foothill Transit electric bus station and wiring/electrical inspection costs from utility-scale PV plants.

- PMI cost: **$8,000/yr**
- PV wiring/electrical inspection: $5/kW-yr → cost for 9.4-MW station: **$27,000/yr**

Inverter maintenance

We used utility-scale solar inverter O&M costs as a proxy for EVSE maintenance costs.

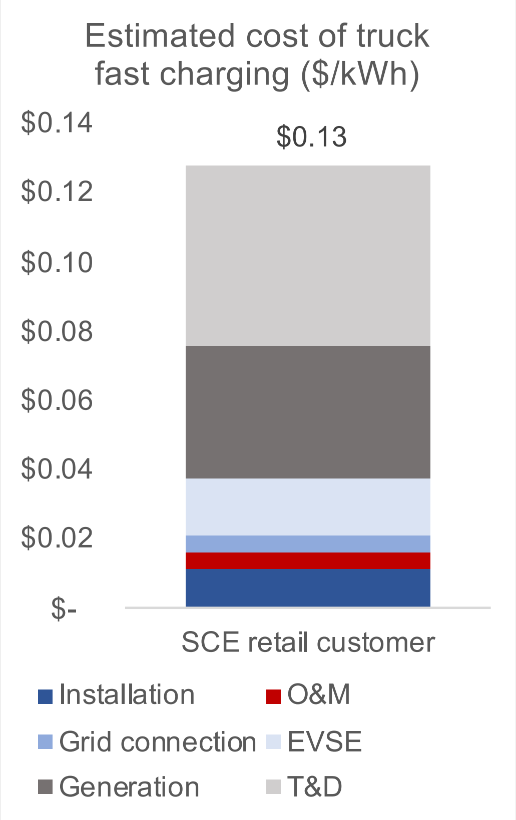
- Inverter O&M: $7.50/kW-yr → cost for 9.4-MW station: **$70,000/yr**

Structural maintenance

We estimated wear and tear on the EVSE plastic housing based on industry interviews.

- EVSE housing lifetime: 10,000 cycles → **0.6 years/EVSE**
- EVSE housing replacement cost: $2,000/unit → total **$6,000/yr**

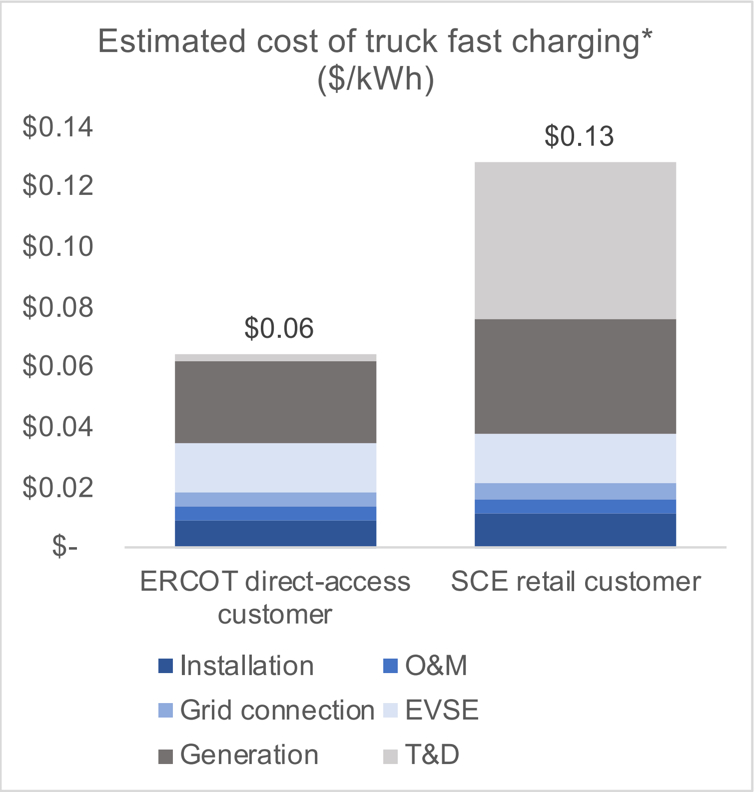
Estimated O&M cost of 9.4-MW charging station: $100,000/yr



Total cost of charging station

The total cost of a charging station is $6.6-7.3M, plus $100,000/yr; this is less than $0.04/kWh

- The total cost of an electric truck fast charging station is estimated to be **$6.6M (Texas) - $7.3M (California), plus $100,000/yr in O&M**
- This cost is levelized over:
  - **The lifetime of the charging station** (assumed to be **15 years** except for the grid connection, which is assumed to be **30 years**)
  - **The number of kWh sold** (here assumed to be **22,000/yr** if the station achieves a 33% utilization rate—i.e., all chargers are in use 8 hrs/day at 80% of max capacity)
- Station cost accounts for less than **$0.04/kWh** out of a total charging cost of **$0.06-0.13/kWh** when levelized
- This cost is competitive with diesel trucking, which breaks even with electric trucking at **$0.11-0.18/kWh** charging cost (see next slide)

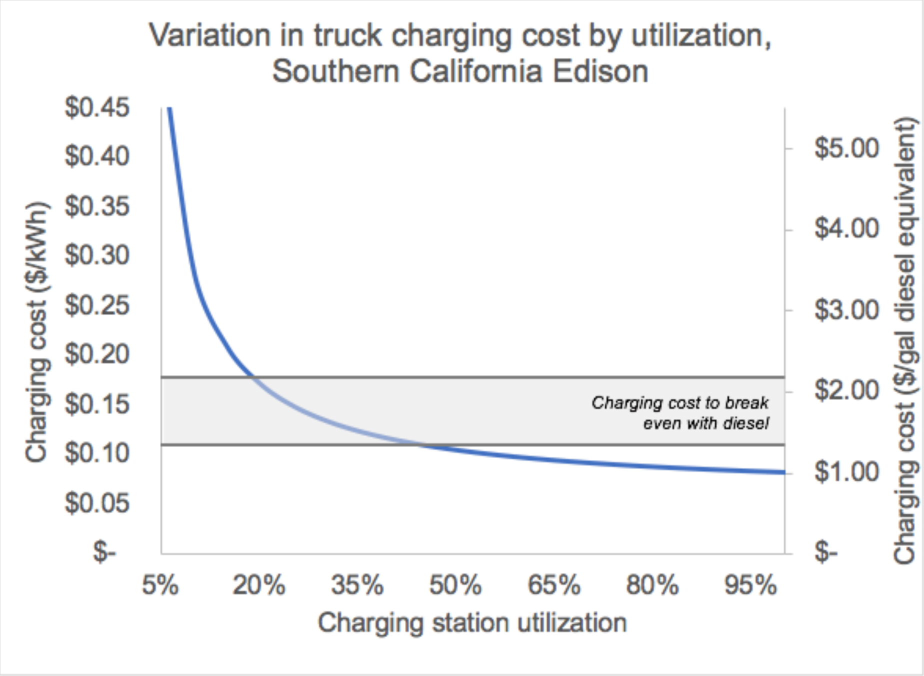


*Includes amortized infrastructure cost at 33% station utilization

Impact of utilization on charging costs

Station utilization rate has a major impact on the cost of truck charging

- **Station utilization rate** has a major impact on the cost of charging
  - Achieving high levels of utilization allows fixed station costs to be spread over a larger number of kWh
  - Lower per-kWh costs increase competitiveness with diesel trucking
- Achieving high enough utilization to break even with diesel at **$0.11-0.18/kWh** is critical to the success of electric trucking
- Truck charging station costs account for less than **$0.04/kWh** at 33% utilization, but rise to **$0.12/kWh** at 10% utilization



**Diesel competitiveness is based on diesel at $3.16/gal, and battery costs between $100/kWh (top of range) and $170/kWh (bottom of range)*

Conclusion

Truck fast charging station costs are estimated at less than $0.04/kWh

- **Decarbonizing road freight is critical**, and electrifying large trucks is becoming a feasible solution
- **Understanding the cost of truck fast charging** is key to planning for road freight decarbonization
- **The cost of truck charging** is driven by the cost of the charging station and the cost of electricity, which vary based on location and electricity tariff structure
- **The cost of the charging station** consists of the cost of the EVSE, grid connection, installation, and O&M
- **Charging station cost** is estimated to be **$6.6M-$7.3M + $100,000/yr**; on a levelized-cost basis, this is less than **$0.04/kWh** (at 33% station utilization)
- **Station utilization rate** has a major impact on the levelized cost of truck charging and, thus, on its competitiveness with diesel